

NONINVASIVE ACOUSTIC-WAVE MICROFLUIDIC DRIVER

Hongyu Yu and Eun Sok Kim

Department of EE-Electrophysics, University of Southern California,
Los Angeles, CA 90089

ABSTRACT

This paper describes a Noninvasive Acoustic-Wave Microfluidic Driver built on a PZT sheet. The driver is based on the acoustic streaming effect and the self-focusing nature of the Fresnel Annular Sector Actuator (FASA). An array of FASAs is produced on a PZT sheet, and set adjacent to a silicon wafer to produce a fast liquid motion (up to 123 mm/s) in a 0.8 mm wide, 9 mm long and 0.2 mm deep channel in the silicon. The self-focused waves from the FASA array propagate through the 200 μm thick silicon, and act on the water contained in the channel. Three kinds of FASA arrays have been fabricated along with their associated channel structures in silicon, and shown to transport the liquids effectively. The experiment results obtained on the fabricated devices confirm the theory and simulation.

INTRODUCTION

Lab-on-chip (LOC) with microfluidic processing capabilities has great potential for biomedical applications. But the fluid transportation in LOC is a challenging problem. A conventional technique is to use an external syringe to push/pull fluids, but such a syringe cannot be integrated with LOC. And heat, electrolysis and flexural-plate waves have been used to drive microfluids with limited success for biomedical applications [1]. It has been reported that focused acoustic waves are effective in generating fluidic motion [2], and Fresnel Annular Sector Actuator (FASA) design can produce excellent micromixing [3]. Thus, we have invented an idea to use an array of FASAs (shown in Fig. 1) to transport fluids along arbitrarily long channels. This paper describes the theory, simulation and experimental results of the FASA fluid driver.

THEORY

The operating principle of FASA is based on the self-focusing acoustic-wave transducer, which focuses acoustic waves through constructive wave interference [2]. In the transducer, when RF power is applied between

the electrodes (sandwiching the piezoelectric film) with its frequency corresponding to the thickness mode resonance of the piezoelectric film, strong acoustic waves are generated over the areas covered by the electrodes. The acoustic waves interfere with each other as they propagate in the fluid adjacent to the transducer. With a proper design of the electrode patterns (e.g., a set of annular rings acting as half-wave-band sources), we can achieve wave focusing without any acoustic lens [2].

With a set of complete annular rings, the acoustic field is radially symmetrical in the planes of the rings. But with the rings broken into segments of various angles, the acoustic field becomes nonsymmetrical in plane, and along with the acoustic streaming effect caused by the acoustic loss, produces steady body force in the liquid to drive fluid flow.

A high-intensity acoustic wave propagating in a medium is absorbed and scattered by the medium. The wave attenuation with a high intensity wave is nonlinear, and causes the medium itself to move. This nonlinear acoustic effect is called acoustic streaming.

The basic cell that we employ for the FASA fluid driver is a 90° FASA on a PZT substrate shown in Fig. 2. The electrode patterns for the top and bottom electrodes are designed to produce a very high lateral steady body force.

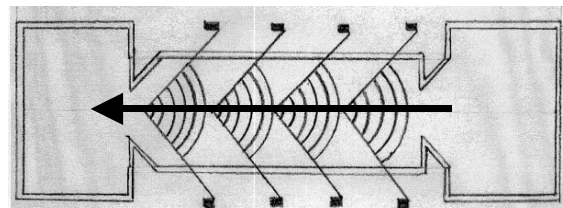


Fig. 1 Top view schematic of the FASA fluid driver based on a linear array of Fresnel Annular Sector Actuator (FASA).

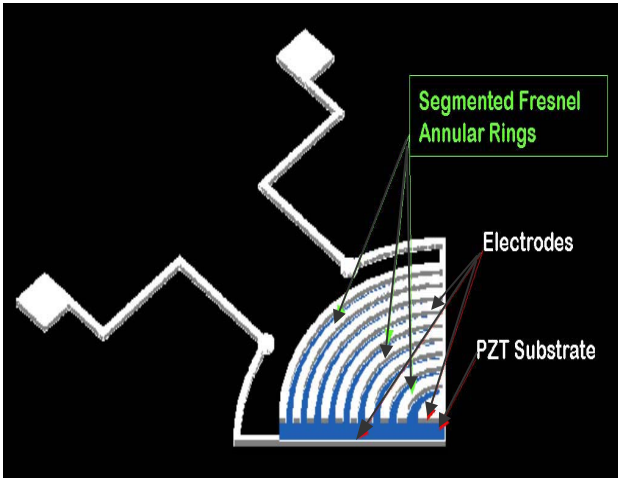


Fig. 2 Cut-away view of the basic cell of the Fresnel Annular Sector Actuator (FASA).

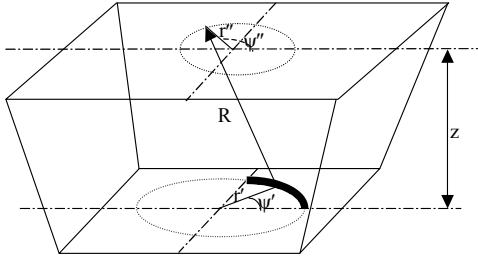


Fig. 3 The notations used for theoretical analysis and simulation of acoustic field in a medium adjacent to the FASA located at the bottom plane.

Referring to Fig. 3 for the notations, the acoustic potential at any point of liquid is given by (with α being the acoustic attenuation constant):

$$\phi(r'', \psi'', z) = -\frac{u_0}{2\pi} \int_{\psi'=0}^{\pi/2} \int_{r'=0}^a \frac{e^{-jkR-\alpha R}}{R} r' d\psi' dr'$$

And from the acoustic potential, we get relative particle displacements as follows.

$$u_{\psi''} = \frac{1}{r'} \frac{\partial}{\partial \psi''} \phi(r'', \psi'', z) \Big|_{\psi''=const, r''=const}$$

$$u_z = \frac{\partial}{\partial z} \phi(r'', \psi'', z) \Big|_{\psi''=const, r''=const}$$

$$u_{r''} = \frac{\partial}{\partial r} \phi(r'', \psi'', z) \Big|_{\psi''=const, z=const}$$

After transforming the cylindrical coordinate to the rectangular, we get the relative particle velocities from the particle displacements as follows.

$$v_x = \frac{\partial U_z}{\partial t} = -U_{z0} \omega \sin \omega t$$

$$v_y = \frac{\partial U_x}{\partial t} = -U_{x0} \omega \sin \omega t$$

$$v_z = \frac{\partial U_y}{\partial t} = -U_{y0} \omega \sin \omega t$$

In order to analyze the acoustic streaming, we use Navier Stokes equation of motions for fluid and the continuity equation [3] shown below, where P , ρ , \bar{v} , and \bar{F} are pressure, density, particle velocity and force, respectively.

$$\bar{F} = \rho \frac{d\bar{v}}{dt} = -\nabla P + \mu \nabla^2 \bar{v} + (\lambda + \mu) \nabla \cdot \nabla \cdot \bar{v}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \bar{v} = 0$$

For FASA devices, there is only one resonant frequency that is useful, and we obtain that $P - P_0 = P_1$, $\rho - \rho_0 = \rho_1$, $\bar{v} = \bar{v}_1$, $\bar{F} = \bar{F}_1$, in which the subscripts 0 and 1 denote the steady case and harmonically varying case with the frequency equal to the FASA resonant frequency, respectively.

Thus we get the steady body force, which will drive the steady fluid flow.

$$\bar{F}_b = \rho_0 \langle \bar{v}_1 \nabla \cdot \bar{v}_1 + (\bar{v}_1 \cdot \nabla) \bar{v}_1 \rangle$$

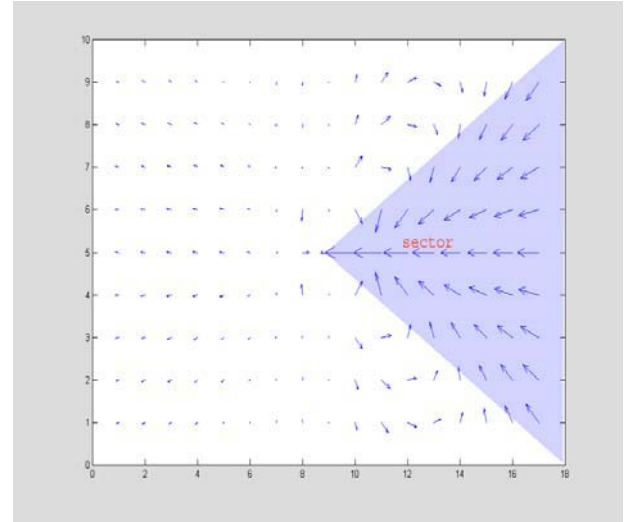


Fig. 4 Top view of the simulated body force at the focal plane (axis unit: 10 μ m)

We have simulated the body force in Matlab using the above equations, and show the body force at the focal plane of a 90° FASA in Fig. 4. For a linear array of 90° FASAs, we integrate the body force in the channel and confirm that the body force will drive the fluid along the direction of arrow (shown in Fig. 1).

FABRICATION

Figure 5 shows the fabrication process for the FASA fluid driver. We use a 192 μ m thick PZT sheet as the transducer substrate. With the front-to-backside alignment

marks, silver electrodes (2.54 μm thick) on both sides of the PZT sheet are patterned such that the top and bottom FASA electrodes overlap each other. The silver is etched with 3M HNO_3 in 35 seconds. The fluid channels are micromachined in silicon substrate using convex-corner protection technique [4]. We have fabricated three different channel types on a 400 μm thick (100) silicon wafer as shown in Fig. 6: (a) linear channel, (b) rectangular close-loop channel, (c) splitting channel that can separate fluid sample into two channels. All these channels are 200 μm deep and 880 μm wide at their top opening. Then we align the channels with the electrode patterns on the PZT sheet, and bond the PZT sheet to the silicon wafer using epoxy (about 10 μm thick). Figure 7 shows the fabricated device.

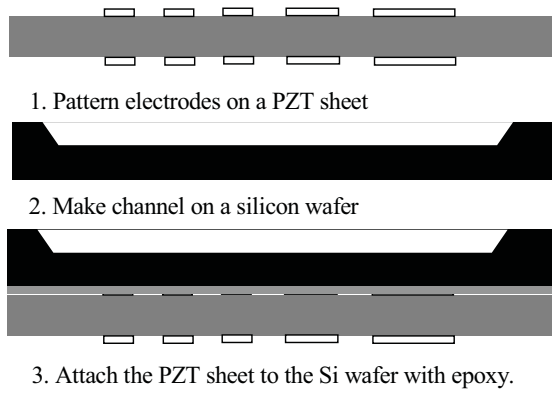


Fig. 5 Fabrication steps of the FASA fluid driver.

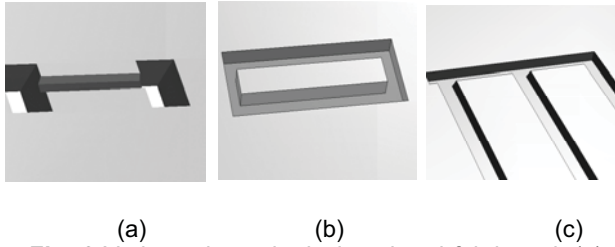


Fig. 6 Various channels designed and fabricated: (a) linear channel, (b) rectangular close-loop channel, and (c) channel for splitting fluids.

EXPERIMENTAL RESULTS

The fabricated devices are tested with a set-up shown in Fig. 8, where 12.5 MHz square wave is modulated with a sequence of pulses from a function generator before being amplified by an RF amplifier and applied to the device. The peak-to-peak voltage of the RF amplifier output is typically about 16 V, and the electrical field across the PZT substrate is about 4.2×10^4 V/m. When we apply a continuous square wave, the series resistance of the electrodes produce significant amount of heat. Thus, we use a pulsed square wave with 120 Hz pulse repetition frequency and on time of 100 μs (which give a duty cycle of 1.2%). And the heat effect is

negligible. Microspheres of 10 μm in diameter are used to facilitate the observation of the liquid flows, the typical of which are shown in Fig. 9. The flow speeds in these three structures are measured to be 7.4 cm/s, 8.5 cm/s and 4.6 cm/s.

A square RF signal has been found to be more effective in driving fluids than a sinusoidal RF signal, due to the fact that a square wave contains more frequency spectrum than a sinusoidal wave. Though the frequency that is most effective in generating acoustic wave is the PZT resonant frequency, it is often difficult to tune the sinusoidal frequency to that resonant frequency due to instrumentation limitation.

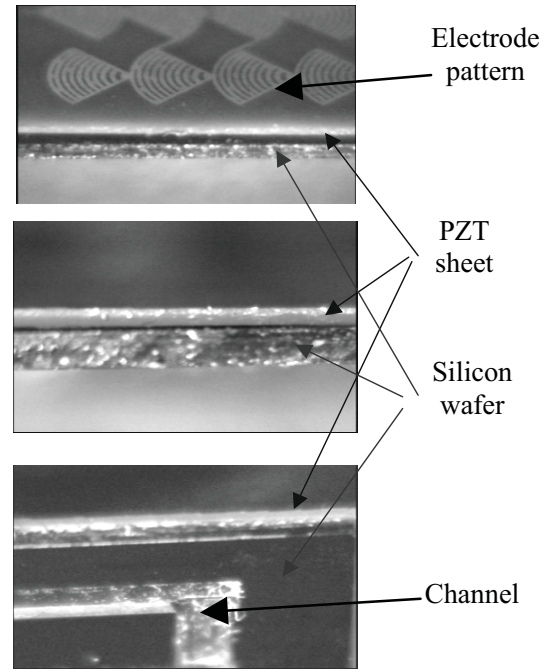


Fig. 7 Cross sectional views of the PZT driver bonded to a silicon wafer containing fluidic channels.

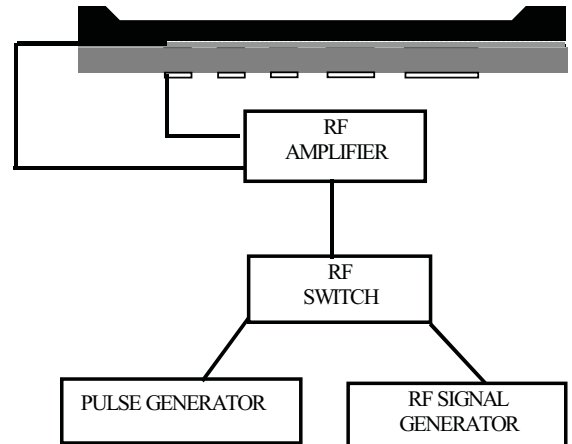


Fig. 8 Schematic of the test set-up.

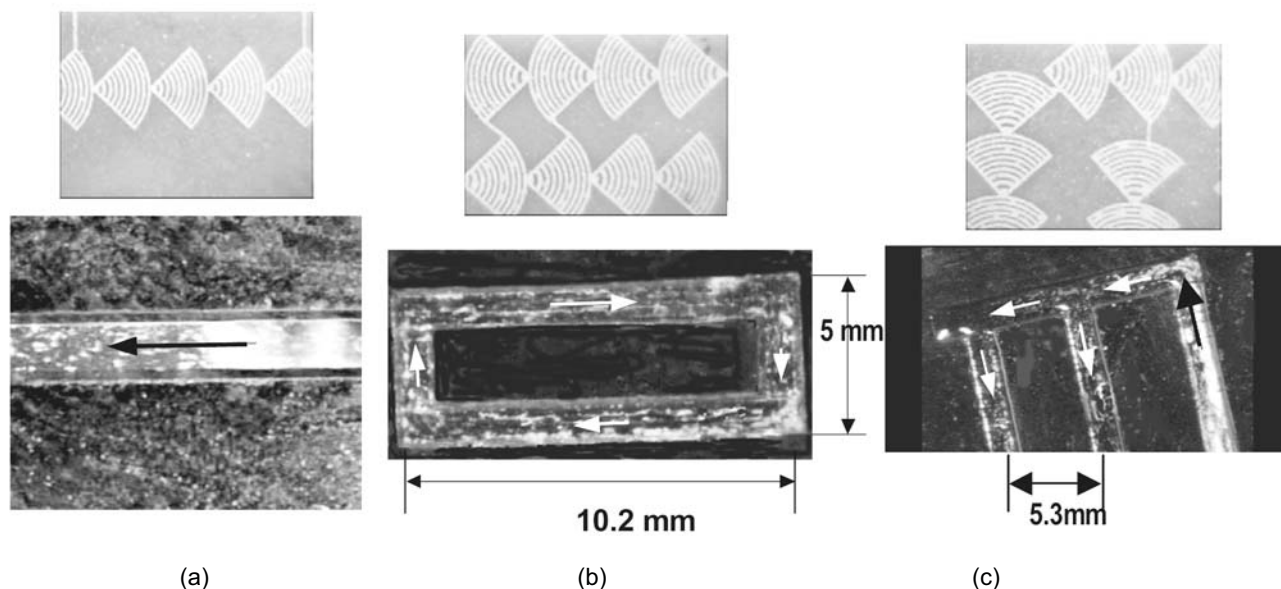


Fig. 9 Snap shot photos of the liquid motions (with microspheres aiding the visualization) in the three types of the channels (fabricated in a silicon wafer) when driven by the PZT FASA array (shown at the top of each photo): (a) in the linear channel, (b) in the rectangular close-loop channel, (c) in the channel for splitting fluids.

When we use anisotropic etching with the convex corners at the channel connecting points, we have observed reflections of fluid flows at the corners, if the connection points are not perfectly smooth and if the fluid flow speed is high. Thus, we use the HNA isotropic silicon etchant to produce a smooth channel connection as shown in Fig.10, and obtain a flow speed as high as 12.3 cm/s.

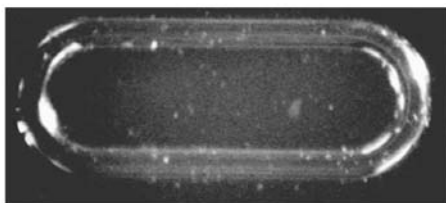


Fig. 10 Circular channel connection

SUMMARY

In this paper, we describe the theory, simulation and experimental results on the FASA-based microfluidic driver fabricated on a PZT substrate. We demonstrate the noninvasiveness of the microfluidic driver by attaching it to a silicon substrate with channels and driving fluids along the channels that are about 200 μm away from the PZT transducer. Fluid flow speed of up to 123 mm/s has been obtained in a 0.8 mm wide, 9 mm long and 0.2 mm deep channel. Since the fluid driver uses strong acoustic thrusts in fluids with negligible amount of heat, it is very attractive in driving temperature-sensitive fluids.

ACKNOWLEDGEMENT

This material is based upon work supported by Defense Advanced Research Projects Agency under contract #N66001-00-C-8094.

REFERENCES

1. C. E. Bradley, J. M. Bustillo, and R.M. White, "Flow measurements in a micromachined flow system with integrated acoustic pumping", 1995 IEEE Ultrasonic Symposium, pp 505-510
2. X. Zhu and E.S. Kim, "Microfluidic Motion Generation with Acoustic Waves," *Sensors and Actuators: A. Physical*, vol. 66/1-3, pp. 355-360, April 1998.
3. H. Wang and E.S. Kim, "Ejection Characteristics of Micro machined Acoustic-Wave Liquid Ejector," *The 10th International conference on solid-state Sensors and Actuators* pp.1784-1788.
4. T. Uchida, T. Suzuki, and S. Shiokawa, "Investigation of Acoustic Streaming Excited by Surface Acoustic Waves," 1995 IEEE Ultrasonics symposium pp. 1081-1084.
5. J. Kwon and E. S. Kim, "Microfluidic Channel routing with Protected Convex Corners," *The 11th International conference on solid-state Sensors and Actuators* pp.644-647.